PATH Oxygen (O_2) Concentrator Project

EXPERT ADVISORY GROUP (EAG) MEETING SUMMARY

WEDNESDAY, AUGUST 13TH - THURSDAY, AUGUST 14, 2014

PATH, SEATTLE, WA

Attendees

Austin, Glenn	PATH	gaustin@path.org
Black, Jim	University of Melbourne	jim.black@unimelb.edu.au
Delarosa, Jaclyn	PATH	jdelarosa@path.org
Duke, Trevor (by phone)	University of Melbourne	trevor.duke@rch.org.au
Eisenstein, Mike	PATH	meisenstein@path.org
Enarson, Penny	International Union Against Tuberculosis & Lung Disease	pennyenarson@aol.com
Ginsburg, Amy	PATH	aginsburg@path.org
Izadnegahdar, Rasa	BMGF	rasa.izadnegahdar@gatesfoundation.org
Jacobson, Robert	Consultant	jakepsa02@gmail.com
Jeffers, Emily	PATH	ejeffers@path.org
Klugman, Keith	BMGF	keith.klugman@gatesfoundation.org
Mukanga, David	BMGF	david.mukanga@gatesfoundation.org
Peel, David	Ashdown Consultants	ashdownconsult@btconnect.com
Qazi, Shamim	WHO	qazis@who.int
Saxon, Gene	PATH	gsaxon@path.org
Wollen, Alec	PATH	awollen@path.org
Wu, Grace	Boston University	littlehippos@gmail.com
Yoon, Priscilla	PATH	pyoon@path.org
Zaman, Muhammad	Boston University	zaman@bu.edu

Regrets: Mike English, Steve Howie

Meeting agenda

Agenda item	Topic	Speaker(s)
Day 1: Define issues and ideal requirements		
1. PATH O_2 Concentrator Project	Goal, objectives, activities, outputs, timeline	Gene
2. BMGF Pneumonia Strategy	Role of O_2 in BMGF childhood pneumonia strategy	Rasa
3. Use Cases	Use cases and applications of O_2 concentrators Prioritize use cases	Gene
4. Devices, Part 1	O_2 concentrators in the field, uses and failures	Penny
5. Devices, Part 2	Features and limitations of O_2 concentrators	David
Day 2: The way forward and identifying solutions		
6. Power	Power: problems and potential solutions	Muhammad
7. Maintenance	Parts, personnel and repairs	David
8. Devices, Part 2 (continued)	Review Product Requirements Specification	Gene/Grace
9. Knowledge gaps	Prioritizing issues and challenges: technological and non-technological	Glenn

Abbreviations

C	Celsius
COPD	chronic obstructive pulmonary disease
CPAP	continuous positive airway pressure
°	degrees
EAG	expert advisory group
MRC	Medical Research Council
ISO	International Standardization Organization
LRS	low-resource setting(s)
O_2	oxygen
PRS	Product Requirements Specification
SLPM	standard liter per minute
WHO	World Health Organization

Meeting objectives

Oxygen (O_2) concentrators have great potential to impact the treatment of hypoxia in childhood pneumonia in low-resource settings (LRS). Childhood pneumonia with hypoxia has a high risk of mortality and requires treatment with lifesaving O_2. However, O_2 is not always available or accessible, and many health facilities in LRS are faced with insufficient supply. The purpose of convening this expert advisory group (EAG) meeting was to bring together knowledge leaders and active researchers in the area of O_2 concentrators to discuss past successes and current challenges in O_2 therapy and O_2 concentrators for the treatment of childhood pneumonia in LRS; to provide a forum for sharing the latest research and understanding of current issues in the area of O_2 delivery; to foster networking and collaboration; and to contribute to the development of technical specifications addressing the clinical use of O_2 concentrators in LRS based on up-to-date information and lessons learned from the initial phases of the PATH O_2 Concentrator Project. Objectives of the meeting included: 1. gaining an understanding of the underlying causes of O_2 concentrator failure and underutilization; 2. identifying the challenges and knowledge gaps around O_2 concentrator use; and 3. identifying the key device requirements for successful implementation in LRS.

Key questions included:

- What devices are available, which are appropriate for LRS, and what are the challenges associated with their successful use in LRS?
- Which use-cases apply to the need for O_2 concentrators in LRS?
- What are the failure modes of O_2 concentrators in LRS?
- How can current devices be improved to reduce failure and underutilization?
- What solutions exist to address the need for continuous power?
- What are the remaining knowledge gaps?

Prior to the EAG meeting, a compilation of required reading materials was sent to all attendees: meeting agenda, use case variables sheet, test plan, and product requirements specification (PRS). These documents were sent as drafts that were to be revised based on feedback received during the EAG meeting. For further background, optional pre-reading materials sent to attendees included: a landscape analysis of existing O_2 concentrator technologies and alternative power options (conducted by PATH), studies on the performance of current O_2 concentrators (Peel *et al.*, 2013), device limitations (Sa'avu *et al.*, 2014), and implementation (*Enarson et al.*, 2008).

Meeting outcomes

- Acknowledgement that in the context of childhood pneumonia, effective treatment of hypoxia includes the combination of both a method to detect hypoxia and an uninterruptible supply of O_2. Many health facilities in LRS are faced with insufficient O_2 supply—a great danger to critically ill children.
- Of the methods to supply O_2, efforts have been focused on O_2 concentrators due to their cost-effectiveness and potential to expand delivery of O_2 therapy to more remote settings within LRS.
- Recognition among EAG members that the performance of specific O_2 concentrators already on the market are appropriate for use in health facilities in LRS with access to relatively reliable power and under conditions of high heat and humidity. In addition, recognition that these O_2 concentrators are underutilized in LRS.
- Consensus among EAG members on the importance of global recommendations supporting suitable O_2 concentrators for the treatment of childhood pneumonia for purchasers of this technology. This will enable purchasers to procure devices with confidence and suppliers to have a clearer pathway to LRS markets.
- Revision of the PRS for an O_2 concentrator platform to meet the defined use cases with input from EAG members. This PRS will be the basis for recommendations intended to inform manufacturers, academics, innovators and purchasers of O_2 concentrator technologies.
- Substantial knowledge-sharing by EAG members on the root causes of O_2 concentrator failure and poor performance indicate that the lack of reliable sources of power, access to replacement parts, and appropriately trained servicing personnel are important obstacles to the successful use of O_2 concentrators in LRS.
- Agreement among EAG members that the needs for O_2 concentrators should be differentiated between two separate use cases, for example: A) central hospitals in larger cities with access to relatively reliable power, and B) lower level facilities with unreliable access to power and maintenance.
- EAG members recommended the critical need to address the use of O_2 concentrators in locations characterized by intermittent power and lack of access to regular maintenance in LRS.
- Generation of a prioritized list of potential methods to address the use case of unreliable power. Methods include those that reduce the power and energy requirements, improve the efficiency of O_2 delivery, or provide means for storing O_2 or power.
- Identification of knowledge gaps:
  1. a better understanding of the availability of O_2 in LRS;
  2. more studies validating the effectiveness of O_2 concentrators to treat hypoxic pneumonia; and
  3. lack of global recommendations supporting suitable O_2 therapy devices for childhood pneumonia.

Day One: Define issues and ideal requirements

1. PATH O_2 Concentrator Project: Goal, objectives, activities, outputs, timeline (presented by Gene Saxon)

With funding from BMGF, the ultimate goal of this project is to reduce under-five mortality from childhood pneumonia by developing a reliable, robust, and scalable O_2 concentrator platform technology for the treatment of childhood pneumonia at lower level health facilities in LRS. PATH seeks to develop the necessary inputs for the modification or design of a robust and scalable O_2 concentrator platform through the following project objectives: 1. characterization of past success and current challenges; 2. necessary technical inputs for a reliable and inexpensive O_2 concentrator design with robust requirements; and 3. identification of a clear pathway and recommendations for both developers and purchasers of O_2 concentrators intended for the treatment of childhood pneumonia in LRS. Activities include carrying out a landscape analysis to understand why O_2 concentrators are underutilized or fail when used in LRS, engaging partners, performing an engineering analysis to

identify and assess design approaches, and developing product specifications. Outputs produced from this 18-month project will include an updated landscape analysis of O_2 concentrators used in LRS, PRS to capture the key technical requirements for an O_2 concentrator specific to the needs of LRS for the defined use cases, and a set of recommendations to clarify requirements for purchasers, developers, and suppliers of O_2 concentrators.

2. Introduction and overview of BMGF pneumonia strategy: Role of O_2 in BMGF childhood pneumonia strategy (presented by Rasa Izadnegahdar)

The BMGF pneumonia strategy includes funding research to optimize components of the appropriate treatment package required to avert mortality from childhood pneumonia and leveraging policy change in order to increase availability of critical commodities. One priority is to increase appropriate healthcare with a focus on reducing mortality at the frontline and lower level health facilities in the top five high-burden countries. The BMGF Pneumonia Team seeks to reduce under-five child mortality through the delivery of timely and appropriate care with existing interventions, including the development of a robust and scalable O_2 concentrator platform that can accelerate O_2 delivery as part of pneumonia treatment at lower level health facilities. Strategic goals include: 1. understanding the lessons learned and establishing requirements of an improved platform; 2. building the evidence to demonstrate the impact of O_2 provision in LRS; and 3. accelerating product availability and commercialization.

3. Use cases and applications of O_2 concentrators in the treatment of childhood pneumonia (facilitated by Gene Saxon)

To ensure that an O_2 concentrator platform technology is informed by the needs of users and the local context, we sought to define our understanding of O_2 concentrator platform technologies and its applications for hypoxic pediatric pneumonia. Pneumonia occurs worldwide, with the largest burden in sub-Saharan Africa, South Asia, and West Pacific. Pneumonia is a seasonal disease with anywhere from 20% to 90% more cases during 3 to 5 months of the year. On average, hypoxic pneumonia in children under five lasts 2 to 5 days and is treated with continuous, uninterrupted flow of concentrated O_2 (>85% O_2) at flow rates between 0.1 and 4 standard liter per minute (SLPM). However, the ability to supply O_2 is often challenged by a lack of resources, which influences treatment parameters, and the prioritization of which patients receive treatment. EAG members described the challenges associated with the environment, the user, and the user-interface of O_2 concentrators in LRS.

Summary of key topics and questions discussed

Pulse oximetry	Hypoxia is associated with mortality. Identification of hypoxic patients is a key step to providing the necessary O_2 supplementation. However, pulse oximetry is currently underutilized in LRS. It is currently recommended in the pocket book of hospital care for management of common childhood illnesses, Integrated Management of Childhood Illness (IMCI) guidelines, but not in the Integrated Community Case Management (iCCM) guidelines for the community level. Increasing the use of pulse oximetry may further define and clarify the need for O_2 therapy for childhood pneumonia.
Provision of O_2 therapy for hypoxic childhood pneumonia	O_2 therapy is prioritized for under five year old children who have any signs such SpO2 <90%, assessed by pulse oximetry, central cyanosis, inability to drink due to respiratory distress, very severe lower chest wall indrawing, grunting with every breath in young children, lethargy or unconsciousness, or exhibit a respiratory rate > 70 per minute. Treatment involves nasal O_2 delivery for several hours to few days with flow rates varying by condition and age.

Burden of hypoxia and demand for O_2	A statement that explains the universal need for O_2, including when O_2 should be administered, and a better understanding of the burden of hypoxia around the world is important. The proportion of children who present with other illnesses that need O_2 at different levels of care is not fully understood. The burden of hypoxia differs from country to country and from region to region.
Care-seeking behaviors	In a case study in Bihar, private care providers to children with pneumonia were equipped with pulse oximetry and O_2 therapy via cylinders. After successes were shown in this 1.5 year implementation project, the local community viewed treatment as a more desirable form of care, increasing both the interest in and misuse of O_2 therapy. Community members expressed desire for O_2 supplementation even if it was not prescribed.
Effectiveness of O_2 therapy	The delivery of standard case management based on World Health Organization (WHO) guidelines and O_2 supplementation in supportive care was associated with a 30-35% reduction in mortality of hypoxic patients (e.g., Malawi, Papua New Guinea).
High O_2 flow rate and continuous positive airway pressure (CPAP) considerations	There is evidence that higher flows can be safe and effective depending on the patient's condition. In a study conducted in Papua New Guinea among 1000 children, at least 80% children did well with standard O_2 treatment. The remaining 10-20% of children remained hypoxic at the WHO-recommended flow rate treatment. Treatment with higher flows relieved the majority of hypoxia after 12 to 24 hours of treatment. In a trial in Bangladesh, when the WHO-recommended flow rates did not relieve hypoxia, CPAP was administered. CPAP with air and O_2 can be beneficial for neonatal treatment.
Humidification considerations	Room-temperature water bubble humidifiers only provide modest humidification when cold dry O_2 is given via cylinders. Humidification may be less needed when O_2 is given via O_2 concentrators in a tropical environment, as these use atmospheric air. However even using a concentrator, if high flows are used (> 4 SLPM), or if the O_2 deliver method bypasses the nasal passages (such as via nasopharyngeal catheters), humidification is recommended. Without humidification, there is drying of respiratory secretions and impaired function of nasal cilia. Nasal mucosal bleeding or ulceration can also occur if there is inadequate humidification.
LRS environment	High temperature, humidity, dust, and power supply interruption and reliability are often present in LRS which can affect O_2 concentrators in various ways. While studies have demonstrated O_2 concentrators have been used successfully in pediatric wards in LRS worldwide, the O_2 concentrator model should be carefully selected (and evaluated, if possible) to meet the manufacturer's specifications in the field. Not all O_2 concentrator models deliver adequate concentrated O_2 when operating at 40°C/95% relative humidity. Most concentrators have filters which frequently become clogged in dusty environments.
Maintenance and staff	Regular maintenance is important for O_2 concentrators. High staff turnover occurs and makes an adequate supply of trained staff difficult. A device with fewer maintenance requirements is needed in LRS, as it cannot be expected that all health facilities (especially lower level ones) have trained technicians/medical engineers regularly available to perform maintenance.
O_2 concentrator applications	Available O_2 concentrator devices are currently marketed primarily for the chronic obstructive pulmonary disease (COPD) market. This is mostly older adults in homecare settings. Manufacturers are moving towards more lightweight and portable options to meet the COPD market demands. O_2 concentrators are also used for treating hypoxia in pediatric patients and for anesthesia.
Evaluating currently available devices	Rigorous testing of different concentrators is needed to expose inherent failures and inefficiencies in design. It takes a long time to determine if a concentrator is working in the field. It is important to have large-scale and long-term field trials to determine the usability, feasibility and acceptability of O_2 concentrators. In an analysis of O_2 concentrator usage in The Gambia over 7 years (Peel et al.), each AirSep machine was found to be used a median of 1,680 hours per year.

Power challenges	There is limited data on the impact of poor power quality on O_2 concentrators. DeVilbiss manufacturers have said that devices are sensitive and need surge protectors (Enarson). Based on researchers' experiences, devices vary on their ability to withstand power fluctuations, possibly due to design differences in the circuits, valves, compressor, and sieve beds. The power circuit board is likely affected by power fluctuations. International Standardization Organization (ISO) requirements previously did not require testing at simultaneous high heat and humidity conditions. Future device testing should simulate worst case scenarios (e.g., high temperature and high humidity, intermittent use (which can cause condensation), and power fluctuations).
Target use-case	For the purposes of this project, we will focus on the design of an O_2 concentrator appropriate for use at lower level health facilities that provides overnight pediatric admission, neonatal admission, public use, and can be used in 2 to 3 pneumonia cases per week.

4. O_2 concentrators in the field, uses, underutilization, and failures (presented by Penny Enarson)

The stepwise process used to successfully implement a childhood pneumonia program using DeVilbiss 515 KS O_2 concentrators in Malawi was described. The process included developing a comprehensive training curriculum, training staff on device use and maintenance, retraining electromedical department staff on maintenance and repair, and distributing concentrators with spare parts at the time of purchase. Additional manufacturer recommendations to prevent damage to the devices when used in LRS were also followed, including changing filters regularly and installing a surge protector to protect against power fluctuations. DeVilbiss 515 KS concentrators were purchased for the program in 2000 based on the WHO recommendations. When used with flow splitters, they were capable of treating up to 4 children at a time. Major challenges in the implementation of O_2 concentrators in this program included the constant turnover rate of staff due to death and illness, retraining staff due to absenteeism, and a sudden stop in government funding. This study identified that multidisciplinary collaboration and management, ongoing training, pulse oximetry use, and back-up power were all necessary components for successful introduction of O_2 concentrators in LRS.

Summary of key topics and questions discussed

Supply of parts	Clear management of supply chains is necessary to ensure adequate supply of spare parts when needed. In Zambia, spare parts are often ordered but never arrive. In Enarson's work, two years of spare parts, warranties, and training to field technicians by the manufacturer were supplied at the time of implementation. The most commonly used spare parts were sieve beds, valves, filters, and blanking plugs.
Costs	Fixed costs: O_2 concentrators range in price. There are a variety of devices available, and their cost is primarily driven by the insurance reimbursements for COPD patients in the Western market. This market segment has influenced the world markets, and prices bottomed out a few years ago. Recurring costs: nasal prongs and training on maintenance and use account for the greatest costs. Other large costs can be attributed to repairing the devices.
Nasal prongs vs catheters	Nasal prongs are easier to use compared to nasal catheters. In Enarson's work, prongs were preferred due to problems caused by a lack of staffing. They were also cleaned regularly to enable multiple usage. However, nasal prongs are more expensive and limit widespread use in LRS. A design plan for a low-cost alternative was suggested to reduce cost burden of nasal prongs.
Staff	High staff turnover rates due to death and illness resulted in a lack of adequately trained staff, and therefore, a lack of regular monitoring of the devices and equipment failure. Furthermore, retraining staff was difficult. In a five-year post-evaluation study of Enarson's work, only 5 of 15 hospitals reported a trained technician onsite.

Donated equipment	Some problems with donated equipment include no warranty and/or no easy access to spare parts. In some cases, donated equipment may not always be compatible with mains power.
Device failures	Unrecognized failures in concentrators have led to the treatment of patients with room air rather than O_2. Electrical requirements, maintenance, reliable supply chains for spare parts, technical knowledge for repairs, and preventative maintenance continue to limit the use and effectiveness of O_2 concentrators as supportive therapy for childhood pneumonia.

5. Features and limitations of O_2 concentrators (presented by David Peel)

Several case studies around the use of O_2 concentrators in the field including assessments conducted in Egypt (1993), Mongolia (1994-1997), Malawi (2002-2004), Papua New Guinea (2005), and Laos (2011) were summarized. Key messages of the presentation included: 1. Device models should be appropriately selected for the setting's environment, needs, and ability to serve as a standard. 2. Appropriate training is essential. 3. Preventive maintenance and replacement parts are necessary and must be included in the budget.

Summary of key topics and questions discussed

Major limitations of current O_2 concentrators	Current devices may not be electrically robust to meet the power profiles in LRS. Technical knowledge for repairs and preventative maintenance is needed, but not widely possible in current health systems in LRS. Current ISO safety standards are written for COPD patients in homecare settings with good power quality.
Devices used in LRS	O_2 concentrator manufacturers have historically focused primarily on the COPD market. Nonetheless, various brands and models of O_2 concentrators have been used in LRS to treat pediatric patients, including AirSep and DeVilbiss models. Their success in the field depends on a number of factors, including the quality of the machine, availability of replacement parts, and conductance of regular training programs.
Appropriateness of pulsatile flow and portable O_2 concentrators	Most portable concentrators have a pulsatile flow option that delivers O_2 only when you breathe in (the device can sense the pressure change when you breathe). This method of delivery conserves significant O_2 and power. Currently, pediatric wards are interested in neither pulse trigger technology nor portable concentrators. This is due to challenges with the lack of battery power and that children do not produce sufficient negative pressure to trigger the delivery of O_2. Portable O_2 concentrators are expensive and currently not used for pediatric purposes. Nonetheless, Jacobson recommends a stationary device with a portable edition could be explored.
Performance at high temperature and high humidity	In a study by Peel et al. year, 7 different O_2 concentrators were evaluated for their compliance with ISO safety standards and performance at low voltages. A key finding was that several of the devices tested did not output greater than 82% O_2 when tested at the limits of their environmental specification despite being labeled with that capability by the manufacturer.
Contamination	Cross-contamination between patients is likely minimal. Sieve beds are extremely caustic and would kill any bacteria that might enter from entrained air (Jacobson). Current ISO standards specify that O_2 concentrators require a filter of 0.2 µm. Some manufacturers will include additional filters, such as bacteria filters or HEPA filters.

Day Two: The way forward and identifying solutions

6. Power: Problems and potential solutions (presented by Muhammad Zaman)

The availability and access to electricity or power are known challenges in LRS, as is the frequency of poor quality power. Poor quality power includes interruptions (or blackouts), voltage sags (or brownouts), and surges. While O_2 concentrators are sensitive to electrical fluctuations, the potential impact of frequent poor quality power is not

well understood. Fortunately, there are several technological solutions that can be used to mitigate poor quality power via power generation (gas generators, solar photovoltaic systems, microhydroelectricity, uninterruptible power supplies), energy storage (batteries), and power conditioning (voltage regulators, surge protectors, uninterruptible power supplies). Each of these technologies has advantages and disadvantages in regards to cost, power efficiency, and storage capacity. Two ongoing studies of O_2 concentrators running on alternative (non-mains) power include a solar-powered O_2 concentrator (Michael Hawkes, University of Alberta) and an electricity-free O_2 concentrator using a water source (Jim Black, University of Melbourne). Key messages from the presentation included: 1. Power instabilities (interruptions, sags, and surges) create unknown concerns for system components of devices.2. The design of a more efficient concentrator is essential if alternative power sources (such as solar or hydro) will be used. 3. It is important to assess means to reduce the power consumption and improve the efficiency of O_2 concentrators to increase implementation and utilization in LRS.

Summary of key topics and questions discussed

Impact of power quality	Power surges are frequent in Africa and grid power of 220-240 Volts is more aggressive to equipment circuitry. Currently, there are very limited data available on the number of failures related to power. The impact of power fluctuations on the life span of O_2 concentrators is unknown. DeVilbiss manufacturers have acknowledged that the devices are sensitive to poor quality power (Enarson). Possible areas of research include identifying electronic parts vulnerable to black/brownouts and ways to minimize those effects. Possible solutions include voltage stabilizers, uninterruptible power supply, and surge protectors.
Power efficiency	Electrical requirements are generally high due to the inefficiency of compressing air. An estimated 50 to 70 watts per liter of 95% O_2 is needed to power a concentrator.
ISO Safety Standards	The ISO standard for O_2 concentrators was recently amended. An important change in the revised ISO standard is the requirement for the manufacturer to test the device's performance at *simultaneous* high temperature and relative humidity. Prior to the revision, simultaneous testing was not specified. Such conditions may not be as relevant in the COPD market, but is more likely an issue for pediatric treatment in LRS.
Device design modifications that may improve efficiency	The exploration of components that could lead to savings in energy, O_2, and/or power efficiency include volume of sieve beds, alternative compressor systems, improving nasal delivery efficiency, and the storage of O_2 gas and/or energy.
O_2 storage ideas	Manufacturers have built pressure swing absorption systems for hospitals to store O_2 in emergency situations. Another option is to use concentrators to fill cylinders for later use. If combined with a pulsing technology, this system may allow for ambulation. One possible advantage of storing gas in LRS is that a district hospital can become a hub of O_2 supply for other facilities. If considering gas storage, compressing gas has large energy requirements, and therefore low pressure systems could increase efficiency. Cryogenic liquid storage is possible for high density O_2 storage but is impractical in LRS.
Cell phone batteries	Cell phones are ubiquitous in LRS. However, a typical cell phone battery would only provide less than 1% of the total power needed for a typical stationary O_2 concentrator.
Solar power	Solar power is increasingly used in LRS. In South Africa, the government subsidizes energy to stimulate growth, leading to an increase in homes with solar panels. In ongoing work by Michael Hawkes in Jinja, Uganda, the solar-powered O_2 concentrator system consists of 25 solar panels (80 watts each), a 6-battery bank, and a DeVilbiss concentrator (300 watts).The total cost of the system is $18,000. It can support up to two patients at one time.
Non-electricity O_2 delivery innovations	Black and his group explored other non-electricity methods to power the compressor for a completely electricity-free O_2 concentrator.

7. Parts, personnel and repairs (presented by David Peel)

A retrospective study analyzed the available data on O_2 concentrator repair and maintenance over seven years in The Gambia. The Medical Research Council (MRC) managed 27 AirSep O_2 concentrators in 17 facilities. The majority of repair needs were found by technicians during routine maintenance whereas some were reported by other staff during use. The most common repairs (71% of total repairs) were relatively low-cost (only 7% of total spent on repairs) and required low skill level. Expensive and difficult repairs were rarely encountered. Key messages of this presentation included: 1. Preventative maintenance with low-cost solutions resulted in fewer major repairs; 2. Trained and dedicated technicians as well as budget for travel were essential; and 3. Standardization of equipment and replacement parts is necessary.

Summary of key topics and questions discussed

Lifetime	Each AirSep O_2 concentrator averaged 1700 hours of use per year. After seven years of use in The Gambia, 92% of all O_2 concentrators were still working. The average lifetime of the AirSep compressor was 6.1 years.
Training	A 2 to 3 day training course was offered to medical engineers with college educations to perform maintenance and repair. Those that perform preventative maintenance and repair should ideally be hands-on trained with the device. However, even once trained, those trained might not consider maintenance of O_2 concentrators to be a priority in their daily work.
Potential failure modes	Potential failure modes that could be investigated further include the design and material of sieve beds, clogged filters, power circuit board failures and the effects of power, temperature and humidity on the various O_2 concentrator components.
Repairs	Common, low-cost, and low-skill level repairs include filter replacement, battery replacement, faulty O_2 outlet, leaky or faulty tubing, and faulty check valves. Rare, expensive and high-skill level repairs include pressure regulator adjustment, electrical connections, faulty flowmeter, faulty sieve beds (expensive), power circuit board failure, compressor failure (expensive), multicomponent failure (expensive). Multicomponent failures involve one or more repairs.
Local capacity for manufacturing O_2 concentrator equipment	Most O_2 concentrator manufacturers are located in the United States and Europe. There are several manufacturers in China and India. In-country quality standards and policies are variable, and the quality of Chinese and Indian machines needs to be evaluated.
Health system infrastructure	The appropriate infrastructure and health systems must be in place for a technology platform to have a chance at success. This include involvement of the Ministry of Health, availability of government funding to support the purchase, training, and repair of O_2 concentrators, and adoption of pulse oximetry alongside concentrators.
Maintenance programs	While a maintenance system with dedicated medical engineers is key to successful implementation, one should not assume that all facilities that need O_2 concentrators will have access to the necessary resources. Countries face many challenges including how to train personnel and maintain the devices.
Flow splitters and flow meters	Flow splitters and flow meters have presented challenges in maintenance and misuse. Y-connectors divide flow evenly into two outlets, but without measurement of flowrate in either of the split streams. Nozzle-shaped flow meters deliver airflow at specific flow rates. Nurses and healthcare workers are often not adequately trained on proper splitter use and maintenance. Blanking plugs used to control flow rate with splitters are small and frequently lost. Nozzles are also often broken off. To mitigate some of these problems, AirSep developed the SureFlow for pediatric O_2 delivery, which contains five flow meters in a box-like form factor.

Maintenance logs	In Enarson's study in Malawi, hospital personnel were trained to keep maintenance logs for the concentrators. However, when the concentrators were taken to regional or central level biomedical engineering sites for repair, many logbooks were lost and not replaced. This was due to high staff turnover rates resulting in fewer trained individuals still occupying those roles over time. In Peel's study in The Gambia, a maintenance log was managed by the technicians trained at the MRC and records of more than 800 interventions were later analyzed.
Maintenance needs	The design of a more reliable O_2 concentrator device may alleviate the high burden of repeated maintenance and repairs.
Potential maintenance solutions	Potential solutions for mitigating the problems of maintenance and repair of O_2 concentrators include employing modular designs, developing simpler designs for replacement parts, and utilizing local capacity (e.g., mechanics, suppliers).

8. Product Requirements Specification (facilitated by Gene Saxon and Grace Wu)

The purpose of the PRS is to establish high level technical requirements for the design of O_2 concentrators for use in health facilities in LRS. Each requirement is accompanied by a rationale. Overall, the requirements intend to address the specific use of the device and needs of the users. Prior to the EAG meeting, a PRS was drafted (Revision A) based on the findings from the landscape analysis and interviews with subject matter experts. During the meeting, the audience, scope, and content of the PRS were critically reviewed. Key revisions to the PRS included: 1. narrowing the intended environment from health facilities in LRS to lower level health facilities that have intermittent or no dependable power source and inadequate means for maintenance; 2. revising requirements such that they are flexible to innovation; and 3. removing requirements already specified in the ISO safety requirements for O_2 concentrators.

Summary of key topics and questions discussed

Purpose	The PRS document should not obstruct innovation but incentivize users, developers and manufacturers. The requirements should guide development for a more reliable device with the burden of maintenance alleviated such that O_2 concentrators can be made more commonly available.
Use by potential manufacturers	The PRS should enable the O_2 concentrator market to expand. As the mandate of this project is to recommend changes to current models, rigid specification recommendations might deter manufacturers from making changes. For example, manufacturers may be unwilling to develop a device that functions at 40°C and 95% relative humidity, since their main market does not need to operate at those conditions. Furthermore, how developers/manufacturers can be incentivized by the higher requirements of PRS should be considered.
Use by developers and innovators	Specifications should be versatile and not exclude designs or methodologies that are not used with current concentrators, yet achieve the same goal. For example, Revision A described electrical input requirements. However, this requirement excludes innovative work by Black and his team at University of Melbourne on an electricity-free O_2 concentrator. Also, some O_2 concentrators vary in the number of sieve beds and filters.
Prototyping for manufacturer endorsement	Manufacturers are not as aware or accommodating to the product requirement needs of LRS health facilities. Therefore, designing a prototype to show cost-effective feasibility may be needed. Practical inputs on design from the manufacturers during this process will be needed.
Partnering with manufacturers	At the African Society for Laboratory Medicine, they work to improve access to diagnostic equipment in Africa. The African Society for Laboratory Medicine partnered with the WHO and the President's Emergency Plan for AIDS Relief to work with a manufacturer in the U.S. to address typical maintenance issues with HIV diagnostics.

Endorsement by non-profits	The specifications from the PRS document could contribute to the guidance provided by the WHO Medical Device unit on suitable O_2 concentrators which can also inform the UNICEF Supply Division Catalog.
EAG recommended user considerations	Clinicians and facility-based healthcare providers will ultimately be responsible for using the device. They would need to learn the procedure for use and whom to notify about maintenance problems. In order to lower the burden of maintenance, concentrators in LRS should be designed with low maintenance requirements. Simple, modular, designs are ideal. Technicians cannot be reliably expected in LRS to maintain equipment without support from the healthcare worker.
EAG recommended intended audience and scope changes to the PRS	PRS (Revision A) was originally intended for O_2 concentrator manufacturers and the scope was health facilities in LRS with access to power. However, it was decided during the EAG, that there was an unmet need in lower level health facilities with little to no access to reliable power. The scope of PRS (Revision B), edited during the EAG shifted the intended audience of the PRS to manufacturers and purchasers of O_2 concentrators, innovators, and the WHO.
EAG recommended technical changes to the PRS	• Requirements in Revision A based on current models of O_2 concentrators should be clarified. For example, minimum power efficiency requirements were based on the average performance of devices as specified by the WHO Guidelines on O_2 concentrators in the 1990's. • The flow and pressure requirements should be up to 8 liters per minute. • At least two patients need to be connected to a device at one time. Devices may accommodate up to five patients, but at the district level these devices are highly underutilized. We should anticipate that there will be a change in demand. • Do not repeat requirements that are already specified by ISO standards. • For more information, please refer to the edited PRS draft.

9. Prioritizing issues and challenges: Non-technological and technological (facilitated by Glenn Austin)

It was noted that there was already substantial, although incomplete, knowledge on the root causes of failure and poor performance of O_2 concentrators in LRS. Currently available O_2 concentrators may already be suitable for certain use cases in LRS. However, successful implementation depends on availability of a reliable power source and regular maintenance for which several lower level health facilities do not have access. Also, it was identified that more work is needed to validate the effectiveness of O_2 therapy in supportive care for childhood pneumonia. As a result, two suggestions were made. The first suggestion was to conduct clinical trials with the AirSep O_2 concentrator in LRS to establish effectiveness of the device in conjunction with pulse oximetry in treating childhood pneumonia. The second suggestion was to revise the scope of the PATH project to meet the use case of lower level health facilities without regular maintenance and without access to a dependable source of electrical power. In order to achieve this, PATH plans to create a Development Plan to explore possible technological methods to address this use case. To aid with the latter, the EAG brainstormed and voted on a list of issues and research questions that we believe could increase the value proposition of an O_2 supply platform for implementation in LRS.

Prioritized list of research questions and issues	**Number of votes**
1. O_2 storage (e.g., pressure, volume, means).	9
2. Potential energy savings across different components/functions of O_2 concentrators?	7
3. Alternative energy sources (e.g., current vs coming availability of power, free water, wind, solar, etc.)?	5

4.	Who are the users (e.g., market factors, aspirations, desires, country settings, variation, and culture)?	4
5.	What are external power options that work with existing O_2 concentrators vs on-board power/energy sources?	4
6.	What off-the-shelf technologies could work for? (e.g., multiple sieve beds, alternative diameters/materials, lower pressures, learn from portable concentrators, etc.)?	3
7.	How can energy be stored (e.g., gravity, water, new battery technologies, optimizing batteries)?	3
8.	What are alternative O_2 technologies?	2
9.	What is the "system" fit variation in the field?	2
10.	How are the newest O_2 concentrators performing (e.g., failures, reliability, evaluate those not yet tested)?	2
11.	What is the impact of O_2 concentrators and demonstrated evidence of need?	1
12.	What are the market factors related to O_2 concentrators?	0
13.	How much potential is there in O_2 conservation?	0
14.	Clinical optimization for use procedures.	0
15.	Characterize maintenance problems and challenges to identify what approaches reduce maintenance frequency.	0
16.	Field test O_2 concentrators to understand interactions.	0
17.	Evaluate field needs.	0
18.	Evaluate how to break out functions (e.g., remote components)?	0
19.	Local capacity for manufacturing/components.	0

Summary of topics and questions discussed

Key questions around unreliable power and maintenance	How can we improve the specifications of the device to lessen the problems existing in the system? How do we make current devices less susceptible to power fluctuations and increase efficiencies by reducing power requirements?
Solutions identified	Recommendations included investigating the potential technological gains in energy and O_2 efficiency, conservation, and storage to alleviate the burden of maintenance and reliance on power.

Next steps

Based on the EAG meeting discussions, our future activities will focus on the development of a set of necessary inputs for the design of a robust and scalable O_2 concentrator platform appropriate for use at lower level health facilities in LRS characterized by *intermittent power* and *a lack of access to regular maintenance*. Because current O_2 concentrators do not operate in the absence of reliable electricity, and require regular maintenance typically not available in LRS, our strategy is to investigate design improvements relevant to power and O_2 delivery efficiency, generation, storage. There is a critical need for creating global policy guidelines around the use of O_2 concentrators for treatment of childhood pneumonia in LRS for manufacturers and purchasers of O_2 concentrators globally. Findings from our future investigations will be disseminated among manufacturers,

academics, and innovators. We envision that focusing on ways to improve access to O_2 concentrators for use in lower level health facilities in LRS with the capacity to admit a patient overnight has the most potential to address the burden of hypoxic childhood pneumonia in the near-term.